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RESEARCH MEMORANDUM

FUNDAMENTALS OF A METHOD FOR EVALUATING RAIL NET CAPACITIES (U)

T. E. Harris
F. S. Ross

RM-1573

October 24, 1955

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ACKNOWLEDGEMENTS

The applicability of the method proposed in this paper depends largely on the use of suitable working schemes. The authors wish to acknowledge a great deal of help along these lines from their colleagues at RAND.

The examples given in Sec. V were solved by means of a method due to A. W. Boldyreff, who was very active in devising simple and rapid techniques. Thanks are due to G. B. Dantzig for assistance in formulating the problem, and to G. B. Dantzig, L. R. Ford, and J. T. Robacker for work on methods. Particular thanks are due to D. R. Fulkerson for continued work on methods and for initiating and carrying out much of the theoretical work. Acknowledgement is also made to N. H. Rescher, F. B. Thompson, and a number of others, for helpful discussion of related work.

The authors also wish to acknowledge the helpful advice of Mr. Francis E. Armbruster and Mr. William W. Lytzen, AFOIN, Headquarters, United States Air Force.

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SUMMARY

Air power is an effective means of interdicting an enemy's rail system, and such usage is a logical and important mission for this Arm.

As in many military operations, however, the success of interdiction depends largely on how complete, accurate, and timely is the commander's information, particularly concerning the effect of his interdiction-program efforts on the enemy's capability to move men and supplies. This information should be available at the time the results are being achieved.

The present paper describes the fundamentals of a method intended to help the specialist who is engaged in estimating railway capacities, so that he might more readily accomplish this purpose and thus assist the commander and his staff with greater efficiency than is possible at present.

The ability to estimate with relative accuracy the capacity of single railway lines is largely an art. Specialists in this field have no authoritative text (insofar as the authors are informed) to guide their efforts, and very few individuals have either the experience or talent for this type of work. The authors assume that this job will continue to be done by the specialist.

It is even more difficult and time-consuming to evaluate the capacity of a railway network comprising a multitude of rail lines which have widely varying characteristics. Practices among indivi-

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duals engaged in this field vary considerably, but all consume a great deal of time. Most, if not all, specialists attack the problem by viewing the railway network as an aggregate of through lines.

The authors contend that the foregoing practice does not portray the full flexibility of a large network. In particular it tends to gloss over the fact that even if every one of a set of independent through lines is made inoperative, there may exist alternative routings which can still move the traffic.

This paper proposes a method that departs from present practices in that it views the network as an aggregate of railway operating divisions.* All trackage capacities within the division are appraised, and these appraisals form the basis for estimating the capability of railway operating divisions to receive trains from and concurrently pass trains to each neighboring division in 24-hour periods. The foregoing appraisal (accomplished by the expert) is then used in the preparation of comparatively simple work sheets that will enable relatively inexperienced assistants to compute the results and thus help the expert to provide specific answers to the problems, based on many assumptions, which may be propounded to him.

The paper describes, in considerable detail, the organization of large railway systems; it points out that the operating division is, universally, the basic railway operating unit.

* Or systems (see page 12).

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Present estimating practices are briefly described, and the proposed method is discussed in detail. It is then illustrated by applying it to the railway network of Western Russia and her satellites, and determining the over-all capacity of that network under several specific sets of assumptions made by the authors.

The appendix describes in detail how the work sheets can be used in solving a specific problem.

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I. INTRODUCTION

PURPOSE OF THE PAPER

The purpose of this paper is to present the fundamentals of a method for evaluating railway network capacities.

It is not proposed that the highly specialized individual who estimates track and network capacities should be replaced by a novice with a calculating machine. Rather, it is accepted that the evaluation of track capacities remains a task for the specialist.

Such specialists are few in number and their knowledge has been acquired through long experience. Their end product is limited by the human factor. Long and arduous hours of research and computation are essential before they can make estimates which are of value.

This fact, however, is of small solace to the commander and his staff who are faced with countless problems when planning for or conducting an active campaign. They want to know the probable results of several plans of action and they cannot wait for the specialist to compute the details.

It therefore follows that a method that will assist the specialist to furnish more rapid and equally accurate estimates, by utilizing the services of relatively untrained personnel in computing results based on data he provides, should increase his output. This in turn will aid the commander and his staff in obvious ways.

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Specifically it is proposed to provide this specialist with a method that will assist him to furnish the commander and his staff with timely estimates of results to be expected from each of several alternative plans of attack on a rail net.

The method might also assist in evaluating, during the actual waging of a campaign, the effects of railway interdiction.* However, in this connection it is fully recognized that the difficulties inherent in obtaining, evaluating, and disseminating intelligence would limit the usefulness of the method in direct proportion to the information placed at the disposal of the particular specialist concerned.

PROPOSED METHOD

Once the capacities of individual pieces of track of a rail network have been evaluated there remains the problem of evaluating the over-all capability of the network. Moreover, it is highly desirable to be able to make this evaluation rapidly and for many varying sets of assumptions. For example, many different assumptions can be made about the sources of supplies and the destinations to which they might be sent, about the relative proportions of the network which are available for military as opposed to civilian traffic, and about the reductions in capabilities that might be achieved by various plans of air attack or by other means.

* The term "interdiction" is used to mean the interruption of railway movement by the use of any form of air power.

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As far as the authors are aware, no definite method has been proposed for handling such problems. The present paper discusses a method which consists essentially of three steps:

1. In order to reduce the problem to manageable size, it is proposed that the rail network should be considered as an aggregate of operating divisions rather than as an aggregate of lines, junctions, or other elements. Reasons will be advanced as to why this seems a realistic procedure, fitting in with the actual organizational structure of the rail system.
2. Total train capacities between each pair of adjoining divisions are estimated.
3. Any of several simple procedures (one is discussed briefly in an appendix to this paper and others are discussed in the references) can then be applied to estimate the maximum flow through the network and to establish traffic patterns.

The authors wish to avoid making specific assumptions about the possible importance of rail interdiction in any future European war, especially one where thermonuclear weapons are used. The point of view adopted here is that some types of wars have been envisaged - for example, wars with limitations on weapon types or tactics - where land transport would be very important. In any such war in Europe the rail network of Eastern Europe would be an important target. It therefore appears reasonable to illustrate the method by applying it to the Eastern European rail net.

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The method is not completely developed. It requires further study to attempt to incorporate into its procedure a means by which storage, terminal capacities, and short delays can be more realistically assessed before it can be considered as fully capable of application to all situations. However, the authors believe that, even in its present form, the method adds to a better understanding of the complicated Eastern European rail net, its capabilities, and its vulnerable areas. (See Secs. IV and V.) It is hoped that its circulation among interested personnel will lead to improvements.

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II. THE ESTIMATING OF RAILWAY CAPACITIES

The evaluation of both railway system and individual track capacities is, to a considerable extent, an art. The authors know of no tested mathematical model or formula that includes all of the variations and imponderables that must be weighed.* Even when the individual has been closely associated with the particular territory he is evaluating, the final answer, however accurate, is largely one of judgment and experience.

The reason for this condition can probably be best explained by analyzing what the problem entails. No two railway lines are identical; hence the capacity of a system can be evaluated only after due consideration has been given to numerous factors which affect its capacity. Among these factors, the following must be evaluated to arrive at a reasonably accurate estimate:

1. The physical characteristics of the territory in which the system operates and the engineering skill and the costs assumed in its construction. Such an estimate must consider primarily the system's gradients and the minimum radii of its curves.
2. The number of locomotives available, their tractive capabilities, and their mechanical condition.
3. The numbers and location of terminals and passing tracks, including the ability to review, inspect,

* Various formulas have been proposed, and the situation may change in the future.

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store, and forward trains.

4. The size, capacity, amounts, availability, and mechanical condition of rolling stock.
5. Type of road bed construction and weight of rail.
6. The relative skill of personnel involved and labor practices that affect operations.
7. Weather.
8. Operating facilities, including water stands and their capacities; fueling facilities; type of fuel used and its availability.
9. Repair facilities for locomotives and rolling stock.
10. Communications.
11. Marshalling yards.

Given reliable data relative to the foregoing items, there are quite a few individuals who are capable of estimating, with considerable accuracy, the number of trains that a given system can move under normal operating conditions.

However, there is nothing normal about war. Hence, evaluating the capacities of a system while it is being subjected to bombardment by air power will always be a difficult undertaking. Additional consideration must be given to the following:

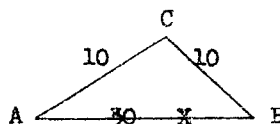
1. The territorial extent of any system as a factor in passive defense.
2. The effect of the weapons used.
3. The flexibility of operation, arising from the presence of alternative lines, and the terminal capacities that

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limit operations. Cases will frequently arise where the mere cutting of a rail line will not stop the movement of trains one would expect. For example, in the diagram which follows, A and B are connected by two lines, one direct and one via C. At first



glance it appears that 40 trains can be passed between A and B on the two lines. If the line AB is cut at X one might surmise the traffic would be cut to 10 trains. However, it is also true that the terminals at both A and B must surely be able to handle 40 trains per day. Hence it may be entirely practicable to pass in excess of 10 trains between A and B via C although it is highly improbable that the entire 40 could be so moved. Perhaps 15 to 18 trains could be moved over this route.

4. The ability to recover from the effects of damage inflicted by military operations. Such ability will depend on a number of factors, among which may be listed the following:
 - a. The availability of the materiel and personnel necessary to effect needed repairs, including the ability of the personnel involved to adopt field expedients.

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- b. Terrain conformation at point of damage, with particular attention to the feasibility of effectively constructing a bypass.
5. Interdiction of personnel, which inflicts casualties and interrupts repair work.
6. The willingness of the personnel to waive operating safety factors.

A resume of the foregoing factors will verify the contention that the problem of estimating track capacities is subject to many interpretations. The specialists engaged in this work, even when provided with good basic data, still face a formidable task; and, what is most important, the more complex the network being analyzed, the more difficult the mission becomes.

However, the commander and his staff face not only this task but many more which must be considered at the same time, if the commander is to get the most out of the means at his disposal. He therefore is entitled to receive reasonably accurate and timely answers regarding results he has achieved by past actions, and further to know what results he can expect to achieve by each of several alternative plans he may be considering.

The specialist, given the time, can supply answers commensurate with his ability; but there are not enough hours in the day for him to supply timely answers to all the logical questions which constantly arise. The proposed method is designed to meet this need. It is believed that, given a few aides who can add and subtract,

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the proposed method will help the specialist fully to meet the
commander's needs and to supply him with timely answers.

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III. THE GENERAL CHARACTERISTICS OF RAILWAY ORGANIZATION
AND OPERATING PRACTICES

Let us examine briefly the general characteristics of railway organization and operating practices in order that we may visualize a network in operation and understand in a very general way how it functions, for this understanding is necessary in order to comprehend the proposed method.

The railway industry has been in existence for sufficient time to achieve considerable stabilization in both organization and operating technique. There are at least four reasons why the large nationally and privately owned and operated systems are similarly organized on a functional basis and utilize somewhat similar operating procedure; these reasons are:

1. Many of the systems do not compete and have been quite willing to exchange personnel and operating experience. For example, some of the North American and British systems have been doing this for years. This practice has resulted in the general adoption of better methods, on a wide international scale, when such ideas have been applicable to local conditions.
2. Some of the large systems supplement each other and form parts of larger continental systems in both Europe and North America. Such being the case, the

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'Berne Gauge' (4 ft 8.5 in.) has been widely adopted to facilitate the exchange of rolling stock, thereby effecting more economical operations by avoiding transfer costs and achieving a more rapid movement of traffic. Such practice has in turn led to considerable standardization of parts to reduce spare-part inventories for foreign stock and to expedite repairs.

3. Both the large capital investment inherent in the industry, and the essential sturdiness of equipment, have forced slow depreciation costs and a reluctance on the part of most management to scrap equipment, even when it is over-aged.
4. The limited capacity of one man to supervise personnel and operating details has also been a factor, for it has resulted in territorial organizations that are limited as to size and number of employees.

There are, also, factors which tend to make for considerable differences in operating technique, particularly as between the European and American systems. These factors are primarily economic.

The American systems are relatively long-haul systems when contrasted with the European systems (excepting the USSR). This condition, coupled with the development of the nations concerned at the time the lines were built, has made for basic differences in equipment, traffic density, and dispatching practice.

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The European systems were superimposed on a society that had, to a large extent, reached a population saturation point. Hence facilities were cramped in large cities because of the cost of property. In addition, the economic practices of these nations leaned to short-term credit and small business; therefore low inventories were the rule and the merchants required rapid delivery of package freight. Finally, labor costs were very low. These conditions all contributed to small equipment, short hauls, dense freight and passenger traffic, and relatively low net tonnage per train. In operating technique, the European system utilizes multiple trackage on most main lines and seldom resorts to centralized traffic control and train dispatchers. The use of manual block signals is the rule.

The European systems, being state owned, also have a very decided tendency to make their organizations (discussed later in this chapter) more purely territorial in nature, rather than basing them on main (or trunk) lines. This is probably because no competition exists between main lines. It is quite common for a division (in Europe) to have under its supervision two or more segments of trunk lines operating in the same general direction.

North American railroads, on the other hand, grew up with the Middle West and to a considerable extent prescribed the development of the West. Hence long hauls, heavy equipment, and larger net tonnages per train are the rule. The economic practices are characterized by long-term credit and large inventories of consumer goods and even

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of some heavy industrial equipment. Much of the trackage is single track, and operations are characterized by centralized dispatching and electric block signals.

Fundamentally, however, both European and North American systems, either state or privately owned and operated, follow the same organizational pattern and over-all operating procedure in moving trains from one location to another. Organization is functional and operation follows generally along the lines of centralized control of equipment and facilities with full decentralization of detailed operations. A general description follows.

1. General Offices: These offices operate the system as a whole and are fully staffed to care for the several executive responsibilities inherent in any corporation or activity. The senior officer (called variously the Chairman of the Board, the President, or the Director General) is responsible for, and has full authority to supervise, all phases of the activities of the system. His senior assistants are charged with functional responsibility such as communications, motive power, maintenance of way, traffic, transportation, and fiscal and legal matters. Centralized control of facilities and decentralization of operating details are the basic principles observed.

2. Regional Offices: Large organizations (such as the USSR, French, Santa Fe, Pennsylvania) are divided into regions which operate under the general offices. This is because a general office cannot efficiently handle many operating subdivisions such as the fifty-two systems which comprise the USSR railways. In such

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cases, the senior official is generally termed either a Vice President, General Manager, General Superintendent, or a Deputy Director General. His staff ordinarily is streamlined and quite small, and primarily covers operating functions. Legal, fiscal, and similar functions frequently are omitted. Regions consist of from two to as high as six or seven divisions.

(The recently announced reorganization of the Pennsylvania Railroad has increased the regional offices from three to nine (for eighteen operating divisions), with increased authority being delegated to the several regions by the head office in Philadelphia.⁽¹⁷⁾ The regional headquarters are now organized to correspond to the general office along functional lines. Regions will in reality operate as smaller rail systems, subject to matters of general policy and the allotment of equipment by the office of the President.)

3. Divisions (Systems - Districts): The Division is the basic railway operating unit. Its territory is frequently a normal engine-and-freight-train crew run in several directions.* The senior official, who is generally called a Superintendent, has a compact staff responsible for, and with authority to perform, the basic and detailed functions incident to all phases of rail operations. For example, his master mechanic is responsible for the efficient operation of all repair facilities assigned to the

* The terms "Grand Division," "System," and "District" are often used to designate an operating echelon which exercises control over several freight divisions. The foregoing terms are considered interchangeable for the purposes of this study.

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division for the maintenance of both locomotives and rolling stock. Similarly his roadmaster is charged with maintenance of way; and his trainmaster exercises detailed supervision over all train movement, normally making the constant decisions necessary to adjust and facilitate such movements.

These personnel, operating in a given territory, are intimately familiar with the physical condition of the division, the effects of a given type of irregular weather, and the multitude of details which affect the entire operation. They work in an atmosphere of constant change. Long experience has adjusted them to the unusual; adjustment to compensate for operating irregularities is very rapid, almost automatic, and in a sense routine. Supervisory personnel, coming on shifts, are fully briefed by offgoing personnel as a matter of routine procedure.

Division officials communicate frequently with officials of adjoining divisions and are currently informed on conditions throughout that entire division which might affect their own operations. Trains are passed from one division to another in the most orderly fashion practicable, and adjustments in schedules are made to conform to the state of conditions then existent. These matters are generally handled informally. When, as occasionally happens, division officials communicate to higher headquarters for help (additional motive power, more cars, etc.), they govern their subsequent operations according to decisions rendered by their superiors.

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Thus we find that the railway division is the basic unit around which the whole system operates. Here is where the detailed work is done; trains are originated, dispatched, and moved over the system to their destination; equipment is serviced and repaired; tracks are maintained; and many other details are handled. Super-imposed agencies concern themselves more with reinforcing divisional efforts, shifting equipment, erecting coordination, and matters of policy.

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IV. PRESENT ESTIMATING PRACTICES AND PROPOSED NEW METHOD

ESTIMATION OF NETWORK CAPACITIES

The U.S. Army FM 101-10 (Staff Officers Field Manual)⁽⁶⁾ sets forth, as a sort of rule of thumb for planning purposes, the capacities of single and double track lines. It lists these capacities as 10 and 30 trains each way per day in a theater of operations and sets forth conditions that will affect these capacities. These data are derived from operating experience, primarily in the Second World War in Europe. They are adequate for the purpose for which they are intended, and are also useful as an aid in evaluating the capacities of entire rail nets.

This latter problem may be stated roughly as follows:

Given, a railway network with known or estimated capacities for the individual lines, with certain locations designated as sources or "origins" of supplies and certain other locations designated as "destinations."

Required, to establish a traffic pattern in the network which will enable the maximum amount to be moved, on a sustained basis, from the origins to the destinations, and to determine the value of this maximum.

PRESENT PROCEDURE

The authors do not know of any objective method that has been used to treat this problem fully. Traffic patterns in complex net-

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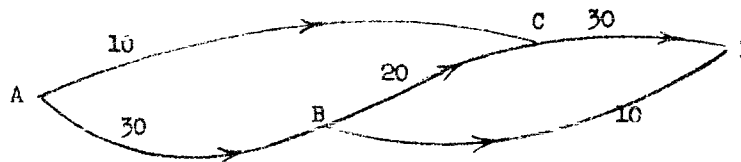
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works such as that shown in Fig. 1 usually grow up over a period of years as the network grows, and adjustments are made as needed. In wartime, entirely new patterns may have to be established.

One practice that has been employed in estimating network capacities is that of picking out a maximal set of independent through lines (that is, any additional through line would have to coincide somewhere with one of the set). Such a set is shown in Fig. 2. Although it is generally customary to pick out only main, or "trunk," lines in such a set (as was done in Fig. 2), it would also be possible to pick out through secondary lines; however, the large number of secondary lines makes it difficult to pick out a maximal set.

This procedure certainly has some value, but it likewise appears to have limitations.

1. The sketch below shows that the through line procedure, if applied literally, may give incorrect answers. The number on each segment represents capacity in trains each way per day.



The line ABCD by itself represents a maximal through-line system, that can deliver 20 trains per day from A to D and return the same number. Alternatively, the two paths ACD and ABD combined represent a maximal set with a capacity of 20. However, the

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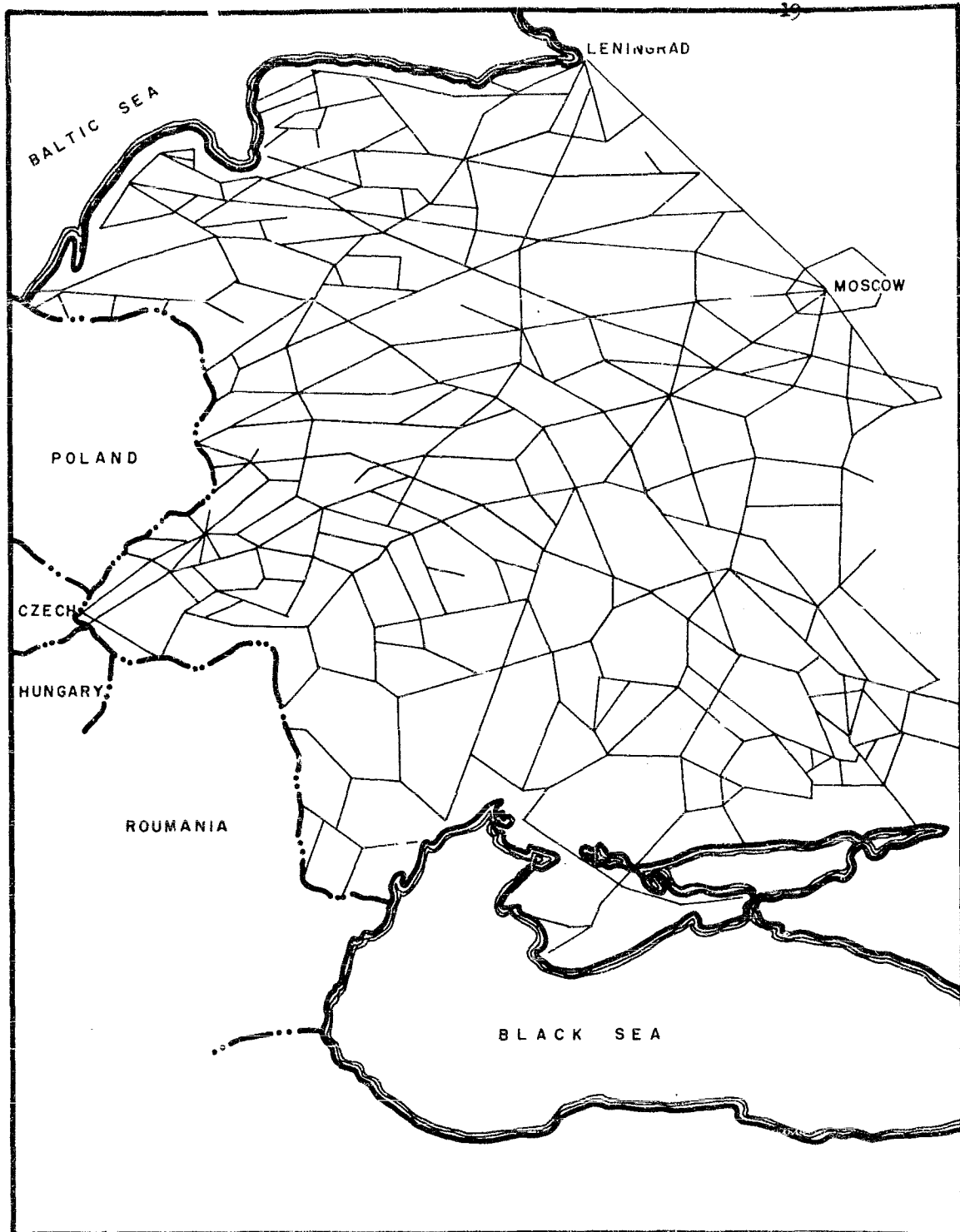


Fig. 1—The railway system of western Russia

Drawn schematically in conventional black and white, this figure shows all lines which make up the rail system of western Russia (as of 1948). No attempt is made to portray single or multiple tracks, or to distinguish between trunk, primary, or secondary lines.

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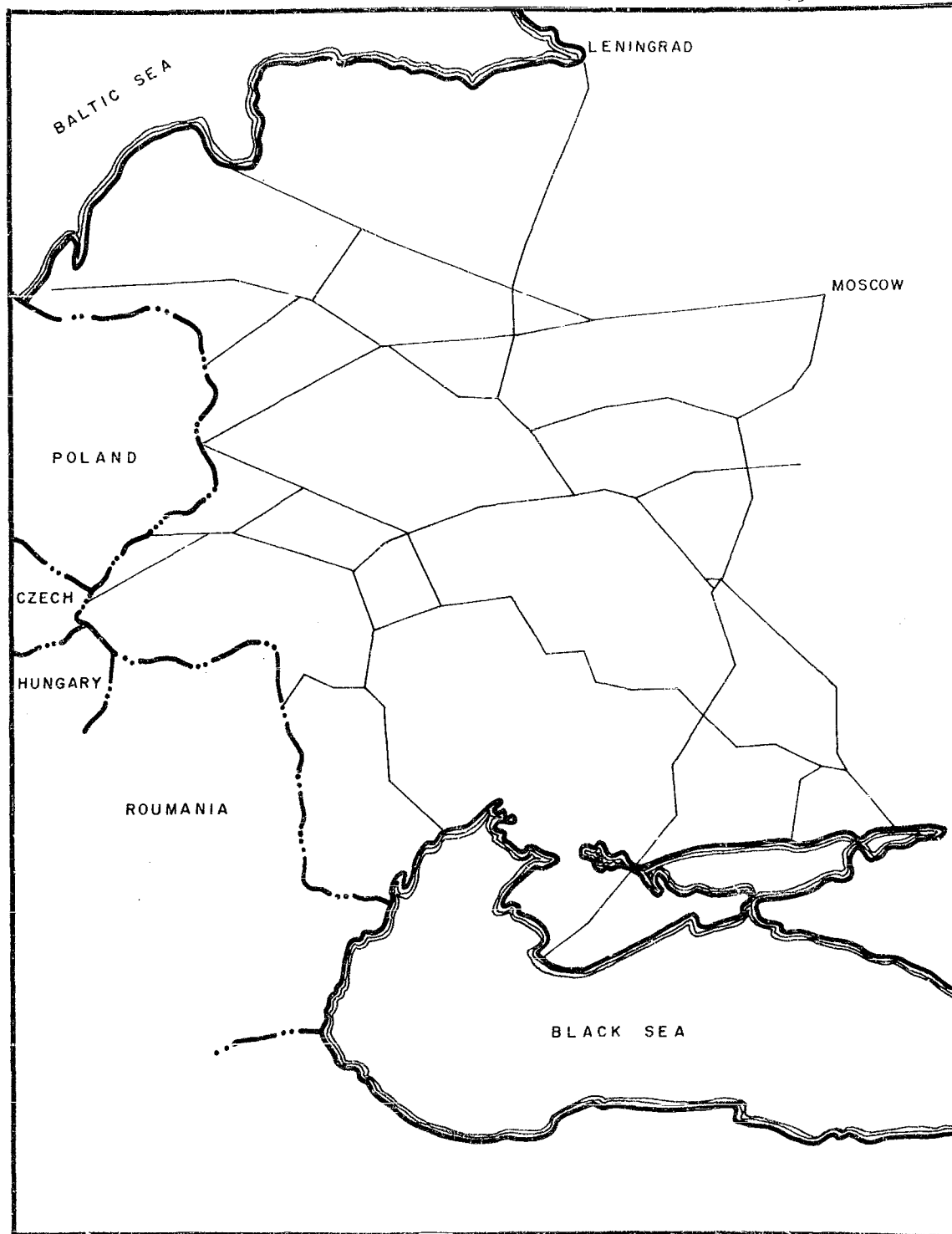


Fig.2—A combination of through railway lines in western Russia

Drawn in conventional black and white. Compare with the network shown in Fig.1 and note the material decrease in lines shown. In Fig.2 only trunk lines are shown

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actual capacity from A to D is 40 trains per day, which can be obtained by saturating each segment with traffic from A to D in the direction indicated by the arrow, and returning the same number in the opposite direction.

This is not to say that any traffic man would go wrong on such a simple example; it is merely to point up the need for something beyond the literal through-line procedure, especially in more complicated situations.

2. As a consequence of either economic or military needs, or for any other reason, origins and destinations may be located in various parts of the network, and parts of the network may have reduced capacities. In such situations it is difficult to pick out meaningful sets of through lines, or to establish traffic patterns quickly.

3. A drawback of the through-line procedure, from the point of view of graphic portrayal of the capabilities of a rail net, is that every one of a set of through lines may be cut and traffic may still flow by alternative routings. For example, each through line in Fig. 2 could be cut and traffic could still move by alternative lines.

A possible alternative procedure would be to apply mathematical methods to work out the exact network capacity from the capacities of the individual lines. This is theoretically possible by the methods of Refs. 1-5, but is not practical for several reasons.

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The calculation would be cumbersome; and, even if it could be performed, sufficiently accurate data could not be obtained to justify such detail. In fact, the very concept of "capacity," applied to an individual segment of track, is vague, depending as it does on conditions assumed about the facilities of the surrounding network.

PROPOSED PROCEDURE

In the previous section certain facts about basic railway organization and operating procedures were discussed, leading to the conclusion that the division is the basic operating unit of a railway system. Therefore in essence it is proposed that the problem be attacked by considering the rail network as an aggregate of divisions.

The proposed method consists of three steps.

1. The rail net is aggregated into divisions.
2. Estimates are made (preferably by a rail specialist) of the number of trains each division can receive from, and concurrently pass to, each of its neighboring divisions every 24-hour period.
3. The over-all capabilities of the network to perform various assigned tasks are then determined by use of one of several available simple schemes of computation.

In the remainder of the present section, Steps 1 and 2 will be illustrated for the rail net of the western USSR and the satellite

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countries. The explanation of Step 3 is deferred to the Appendix, but the results of applying the method to the above rail net, using several alternative sets of assumptions, are given in Sec. V.

ILLUSTRATION OF THE METHOD (Steps 1 and 2)

Figure 3 shows the USSR rail net with the various operating divisions* indicated in different colors. The source of the information for this diagram is Ref. 18, dated 1949.** Similar information was not available for the satellite countries, but assumptions were made about divisional structure, consistent with what was known of the rail systems of the various countries. These assumptions are incorporated in Fig. 3, which is discussed below.

The interdivisional capacities should be determined by a rail specialist who can take the relevant factors into account, given sufficient information. Lacking more specific data, the authors estimated the total capacity between two divisions as the sum of the capacities of connecting lines. The estimates of line capacities were based on general information contained in Refs. 7-16, modified in some instances by individual judgment. These estimates must be regarded as tentative, and subject to revision when better information becomes available. In the table below, capacities are

* Strictly speaking, the term "system" or "district" would be more accurate here than "division."

** This organization has been somewhat modified in 1954 according to information received by RAND after Figs. 3, 4, and 5 had been printed. Since the modification does not affect the method proposed, this paper has been published without revising Figs. 3, 4, and 5. (19)

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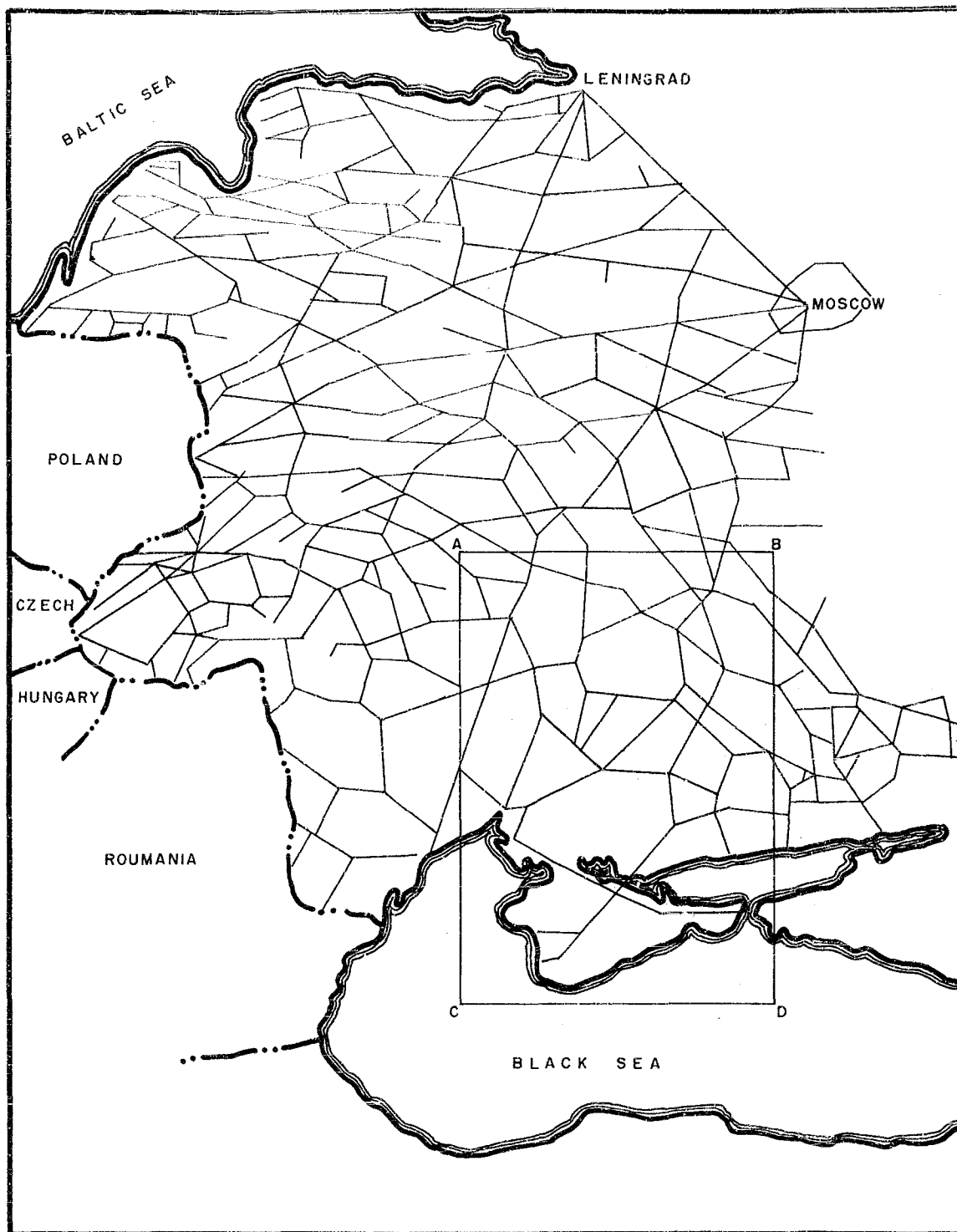


Fig. 3—Schematic diagram of the railway operating divisions of western Russia

This figure is a tracing of Figure 1 in so far as the actual rail net is concerned. The several railway operating divisions, however, are shown in colors.

The outlined area, A, B, C, and D, is enlarged in Figure 4 to illustrate the method of computing the number of trains each way per day which neighboring divisions can concurrently pass and receive.

Estimating the track capacities still remains the task of an expert.

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given in trains (and in tons) each way per day; 'net weight'
refers to the net load per train.

APPROXIMATE CAPACITIES USED

	Double Track	Single Track Main	Single Track Branch
In the USSR			
Trains/day	20-30	8-12	8-12
Net weight	1000 tons	1000	250
Tons/day	20-30,000	8-12,000	2-3,000
In Poland and E. Germany (for trains from Poland)			
Trains/day	20-30	8-12	8-12
Net weight	666	666	250
Tons/day	13-16,000	5-8,000	2-3,000
In Other Satellites and E. Germany (for trains from Czechoslovakia)			
Trains/day	24-30	8-12	8-12
Weight	400	400	250
Tons/day	9,600	3,200-4,800	2-3,000

Figure 4 illustrates how interdivisional capacities were
obtained. Numbers on the lines themselves represent capacities

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in equivalent 1000-ton (net) trains. Numbers in the black boxes represent total interdivisional capacities, obtained by adding the capacities of the individual lines between the divisions.

As an example, Brown can receive from, and pass to, Green a total of 44 trains each way per day: 24 on the double-track line in the north, 8 on the single-track line below, 2 on the single-track line below that, and 10 on the single-track line at the bottom. Note that the limiting factor is sometimes Brown's capacity, sometimes Green's.

Figure 5 shows the result of applying the above method to the entire network under consideration. Interdivisional capacities, in trains each way per day, are shown in boxes.* Figure 5 serves as a basis for carrying out network capacity studies.**

Figure 6 is a work sheet, with capacities omitted so that any desired values may be substituted, to allow for changes in estimates, or changes in actual capacities in the network. In practice it is convenient to reduce all capacities to thousands of tons each way per day, and this is done in the examples shown in Sec. V.

DISCUSSION

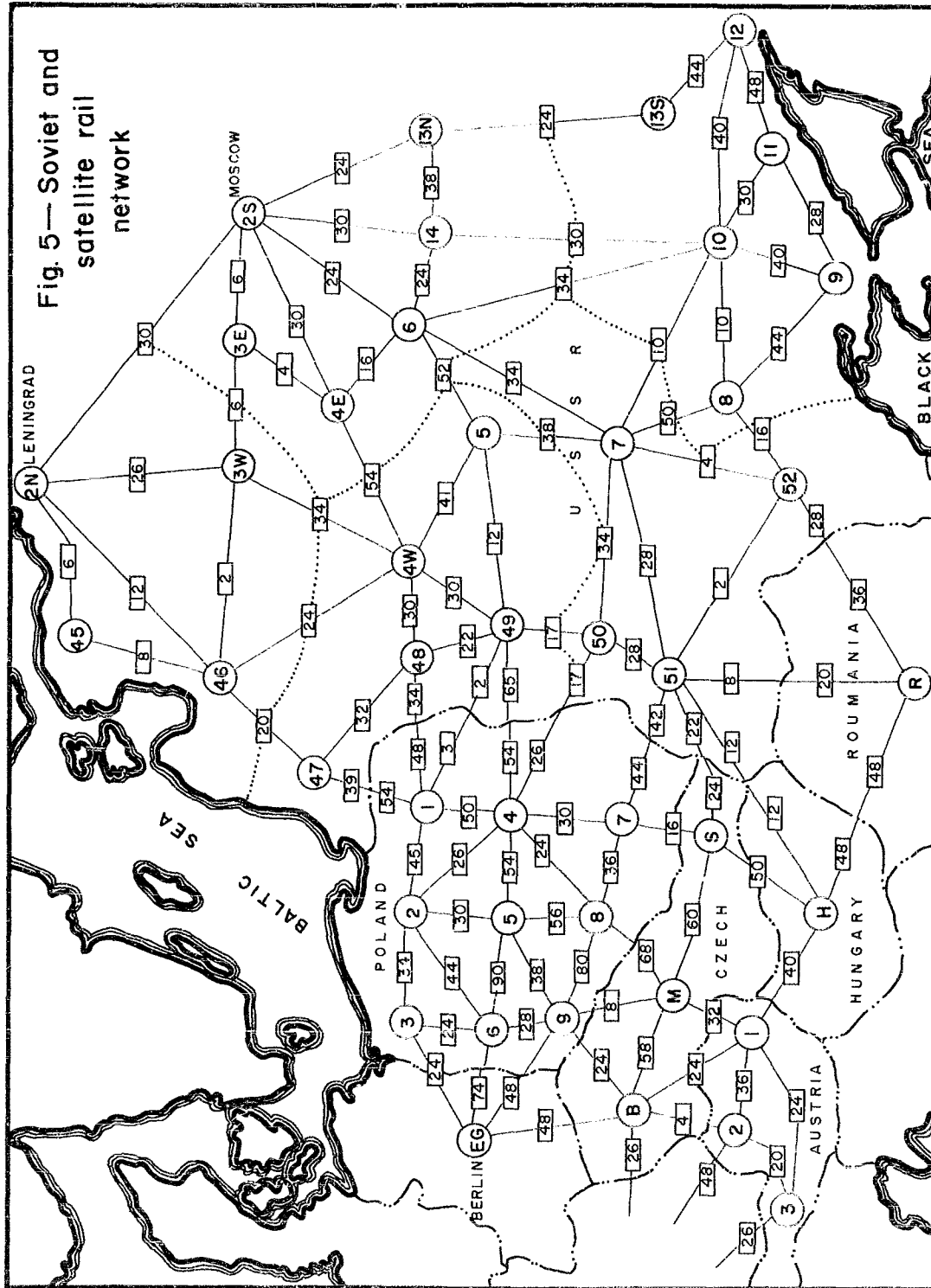
The use of operating divisions as the basic units in treating network problems appears to be realistic in the sense that the

* Net train loads are different in different countries, as explained at the foot of Fig. 5; hence, in working examples, it is more convenient to reduce all capacities to thousands of tons per day, as is done in the examples worked out in Sec. V.

** As mentioned in Sec. V, it is possible to introduce locomotive and rolling stock requirements explicitly into the model.

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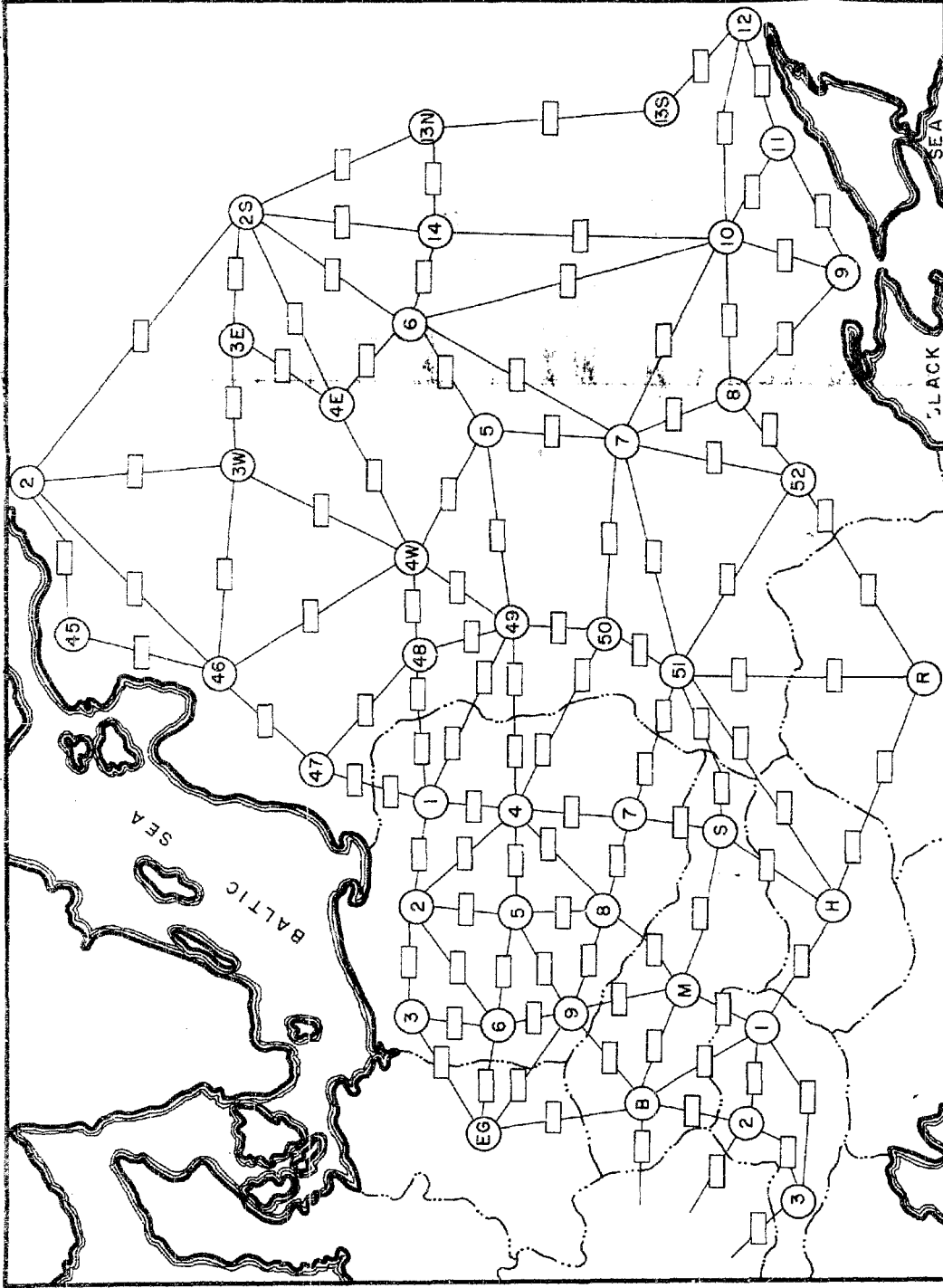
Legend: — International boundary Regional boundaries of the USSR (they are included as a matter of general information)

⑦ Operating divisions. Those located in Russia are believed to be accurately located. Some Russian divisions (2, 3, 4 and 13) are located in two regions and are so indicated. Divisions shown in the satellites are indicated according to the authors' best judgment, since intelligence reports are unavailable. Train capacities in Russia are for 1000-net-ton trains or their equivalent. Train capacities in Poland are for 666-net tons (or the equivalent). Train capacities in all other satellites are for 400-net tons (or the equivalent) except in East Germany. In East Germany, train capacities are those of entering lines. The numbers shown in boxes are total interdivisional capacities.

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Fig. 6—Soviet and satellite railway system: work sheet

Legend: — International boundary
 — Railway operating division
 (8) Capacity: 12 each way per day.
 9 Required flow of 9 per day toward destinations (in direction of arrow) with equivalent number of returning trains in opposite direction
 ← 12 → All capacities in 1000's of tons } each way per day



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chosen units coincide with the basic control centers of the system; should there be need to establish traffic patterns in the particular net under consideration, they would most probably be set up by adjustments made at the divisional level. On the other hand, in choosing the division as a basic unit, the number of elements of the problem is kept within bounds, and computations can readily be carried out.

Another consideration is that the capacity of a rail system depends on more than just individual track capacities. Such factors as yard and terminal capacities, locomotive and rolling stock availability, etc., need to be considered. These factors are largely determined by the capability of the division as a whole, and do not belong to any particular line. They would receive consideration if the interdivisional capacities were estimated by a rail specialist, and could then enter more realistically into the problem than they could if segments of track or through lines were the basic units.

It must be recognized that detailed intelligence information is not always available for estimating interdivisional capacities, particularly under wartime conditions. Furthermore, the proposed method would require modification to deal with cases where there is rapid day-to-day fluctuation in interdivisional capacities. It is believed that, given appropriate data, such modifications could be performed.

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V. STUDY OF THE EAST-WEST TRAFFIC CAPACITY OF THE NETWORK

STATEMENT OF THE PROBLEM

The use of the proposed method will now be illustrated by determining traffic patterns that will produce the maximum east-west (military) tonnage* in the rail network discussed in the preceding section. In order to show the flexibility of the method, the problem is worked under three separate sets of assumptions:

1. The entire network is available for east-west traffic.
2. Part of the network capacity is reserved for economic or other purposes and is unavailable for east-west traffic.
3. Certain divisions are completely inoperative.

These assumptions are arbitrary, and are intended merely to be illustrative.

The results, discussed below, are shown in Figs. 7, 8, and 9. In each of these figures, numbers in boxes represent capacities in thousands of tons each way per day. These numbers correspond to the train capacities shown in Fig. 5. Numbers above the boxes are the required flow, in thousands of tons daily, of westbound traffic, moving in the direction of the arrows. Except at origins and destinations, the westbound traffic entering each division is equal to the amount leaving; also in each case an

* Whether this could be considered "military" tonnage would depend on the loading factors for the types of supplies involved. For convenience, the term "military" will be used.

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equivalent number of eastbound trains move in the direction opposite that of the arrow. A balanced flow is thereby attained.

RESULTS

1. It is assumed that the entire network is available for east-west (military) traffic; no allowance is made for civilian traffic. (See Fig. 7.)

The origins were arbitrarily selected as shown in Fig. 7. (Roumania is one of the origins, although its full outbound capacity is not used.) Destinations were selected as certain divisions in Poland, Czechoslovakia, and Austria, for reasons discussed below.

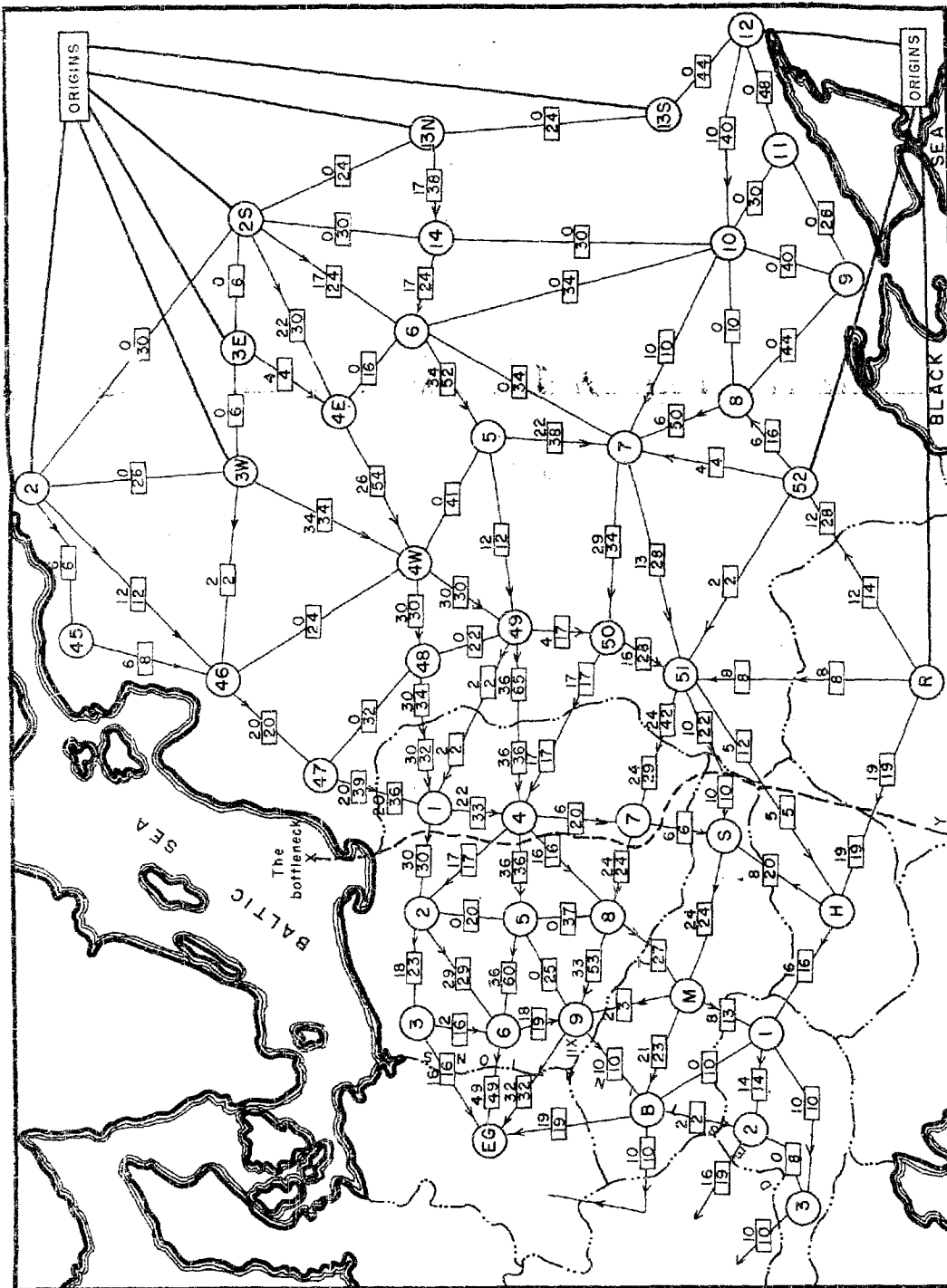
A maximum of 163,000 tons per day can be delivered from origins to destinations by means of the pattern shown in Fig. 7.

The bottleneck that limits the capacity to this amount is shown by the dashed line X-Y.

Remarks on 1. If destinations in Germany were chosen, the maximum amount deliverable would be only 152,000 tons per day because of a bottleneck at the Oder River. This bottleneck is not shown by a separate dashed line in Fig. 7. The same pattern which delivers 163,000 tons to the primary destinations will deliver 152,000 tons to Germany, but the excess tonnage entering Poland must of course be disposed of. This has been done in Fig. 7 by arbitrarily disposing of an excess of 11,000 tons per day at Division 9 in Poland (marked 11X). The bottleneck at the Oder does not have much practical significance as long as the bridges

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Fig. 7 — Traffic pattern: entire network available



Legend:

— — — International boundary

ⓑ Railway operating division

Capacity: 12 each way per day.
Required flow of 9 per day toward destinations (in direction of arrow) with equivalent number of returning trains in opposite direction

All capacities in $\sqrt{1000}$'s of tons } each way per day
Origins: Divisions 2, 3W, 3E, 2S, 13N, 13S, 12, 52 (USSR), and Roumania

Destinations: Divisions 3, 6, 9 (Poland); B (Czechoslovakia); and 2, 3 (Austria)

Alternative destinations: Germany or East Germany

Note: Division 9, Poland

Assumption:
Entire network available for east-west traffic (no allowance for civilian or economic traffic)

Results:
(a) 163,000 tons per day can be delivered from points of origin to destinations.
(b) 147,000 tons per day can be delivered without using Austrian lines.
(c) 152,000 tons per day can be delivered into Germany by all lines.
(d) 126,000 tons per day can be delivered into East Germany without using Austrian lines.

there are functioning, partly because the road net in that area is relatively good, and partly because, in a large east-west movement, much of the tonnage would be dropped off to rear units before reaching the Oder.

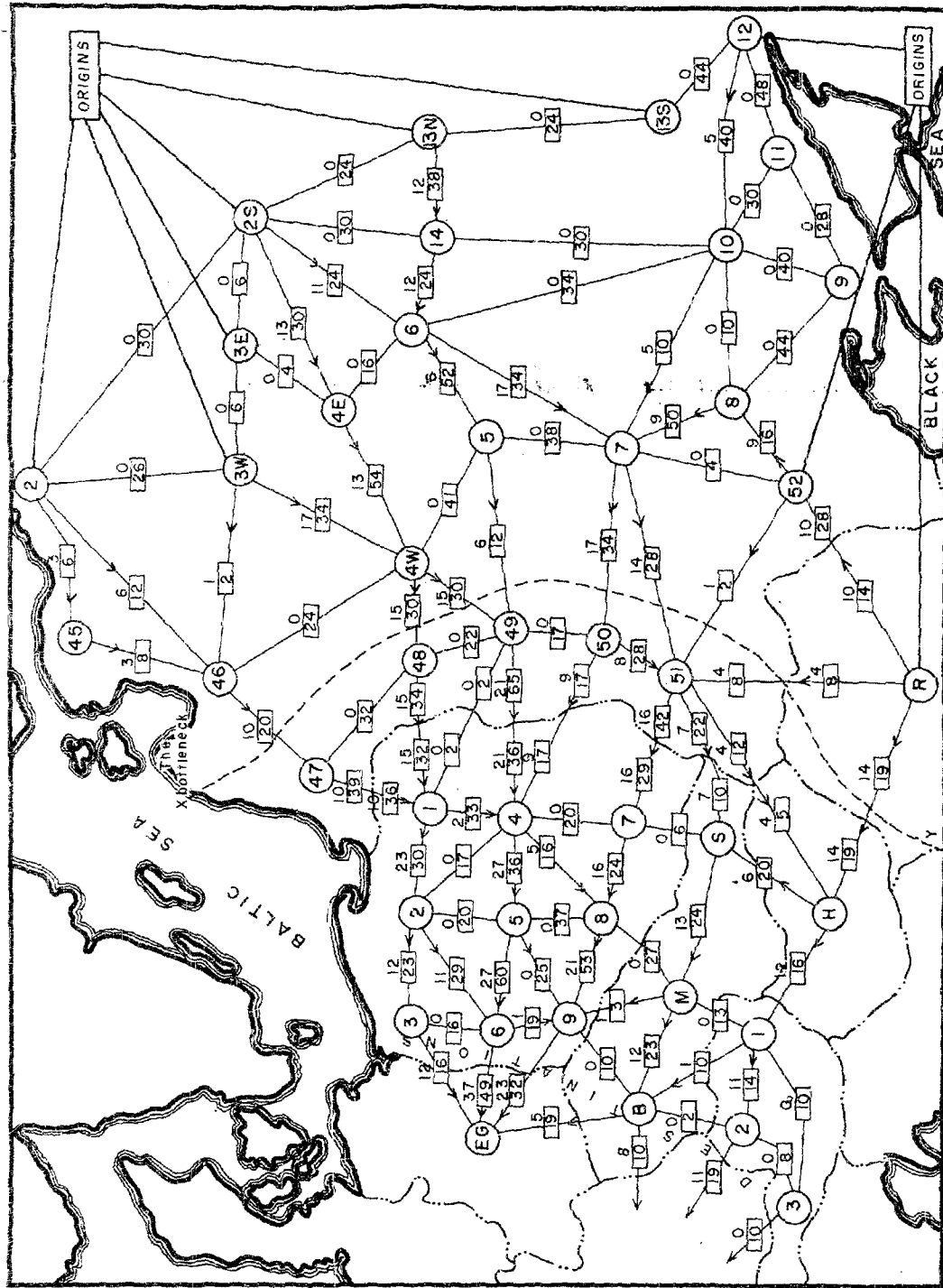
When the entire network is made available for east-west traffic, such movement does not utilize all the east-west capacities except in the divisions whose territories are crossed by the line X-Y. Actually the traffic pattern portrayed utilizes approximately only 75 percent of the Polish, Roumanian, Hungarian, and Czech capacity and only 38 percent of the Western Russian capacity. There are two reasons for this condition. First, much of the network lends itself to north-south traffic and thus dovetails with the present normal interior economy of the territory concerned, since military considerations initially dictated the construction of the rail lines. Secondly, some surplus capacity appears in that part of the east-west pattern which is not limited by the bottleneck.

2. It is assumed that the USSR requires (for economic or other reasons) that in no instance will military east-west traffic exceed 50 percent of an interdivisional capacity inside the USSR, or 75 percent of an interdivisional capacity in a satellite country. (See Fig. 8.)

Origins and destinations are the same as in Fig. 7.

The maximum capacity for military east-west traffic in this case is 96,000 tons per day. A traffic pattern that delivers this is shown in Fig. 9, which also shows the location of the bottleneck.

Fig. 8 -- Traffic pattern: part of network available



Assumption:
Not to exceed 50% of any divisional capacity in USSR to be utilized for East-West military traffic and not to exceed 75% of similar satellite traffic to be utilized for East-West military traffic.

Results:
96,000 tons per day can be moved to destination or Germany. Foregoing movement utilizes 21% of USSR and 40% of satellite capacity in the region shown.

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This flow results in the use of 21 percent of the capacity in western USSR and 40 percent in the satellites.

3. It is assumed that certain divisions are completely inoperative (indicated by hatched lines through the capacity boxes in Fig. 9). Otherwise the full capacity is available, with no allowance for civilian traffic.

A different set of origins was used for this example. The pattern was carried only as far as Divisions 1 and 4 in Poland. From these divisions there is sufficient capacity for further westward movement.

In this case, 103,000 tons daily can be delivered. The Appendix shows in detail how the traffic pattern of Fig. 9 was worked out.

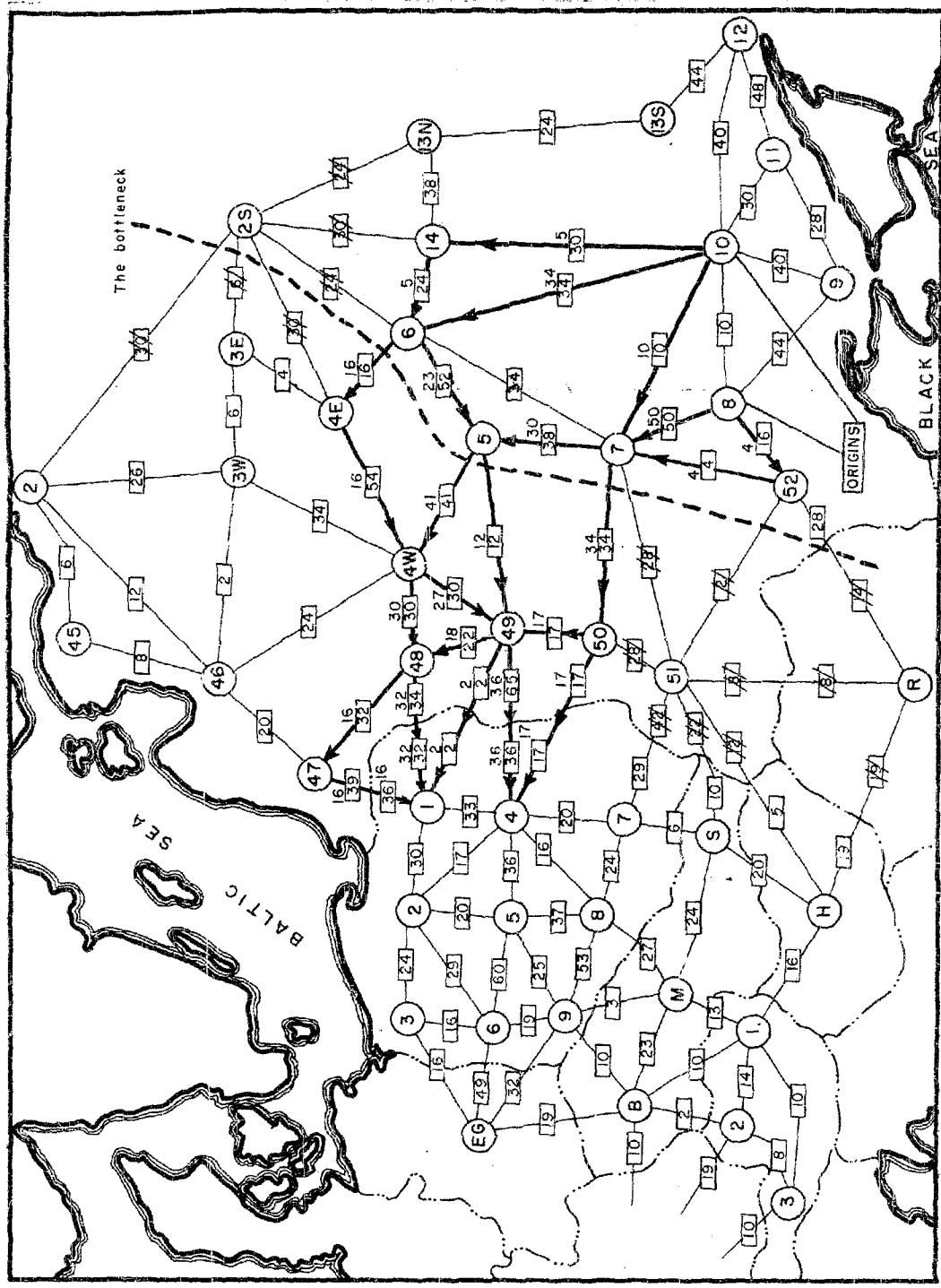
LOCOMOTIVE AND ROLLING STOCK REQUIREMENTS

In the above discussion it was tacitly assumed that there are sufficient locomotives and rolling stock to realize the indicated traffic patterns. It is not difficult to calculate the locomotive and rolling-stock requirements for these patterns, given the appropriate data on requirements per ton-mile. It is also possible to apply methods similar to those discussed in Refs. 1-5 to work out patterns which minimize rolling stock requirements for delivering a given tonnage, or which maximize tonnage delivered with a fixed amount of rolling stock.

Obviously, the use of such equipment would reduce other USSR traffic unless current CIA reports (which indicate a general shortage of such items) are in error.

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Fig. 9—Traffic pattern: certain divisions inoperative



All capacities in $\sqrt{1000}$ s of tons each way per day
103,000 tons daily can be delivered from origins
(divisions 8 and 10 in USSR) to destinations
(divisions 1 and 4 in Poland, thence west or south)

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METHODS

Several methods have been proposed for establishing traffic patterns in networks. Descriptions and related discussion can be found in Refs. 1-5. These methods do not require elaborate computations and can be performed by a relatively untrained person; hence variations in the assumptions can readily be handled.

It is felt that no purpose would be served at the present time by suggesting one rather than another of these methods for use. The criterion for usefulness will be the ability to handle more complex problems.

The patterns in Figs. 7, 8, and 9 were determined by using the "flooding method" of Ref. 1; this appears quite suitable. An illustration of the use of this method is given in the Appendix.

DISCUSSION

Certain assumptions that have entered implicitly or explicitly into the preceding treatment will now be discussed.

1. It has been assumed that the interdivisional capacities do not vary rapidly in time. This seems a reasonable approximation for peacetime operations. In wartime, rapid variations would have to be considered. As mentioned earlier, it is believed that the method can be developed to cover such cases. The situation will then be more complex, and to deal with it at all would seem to require some method of aggregation such as the division method.

2. It has been assumed that the number of trains daily that a division A can pass to a division B is independent of what A passes

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to any third division C. It was pointed out in Sec. IV that capacities are to some extent determined by the capabilities of the division as a whole rather than by individual line capacities. Therefore it is possible that A could pass somewhat more than the normal amount of traffic to B if it restricted traffic to C. Similarly, maximum use of some lines from A to B might interfere with traffic to C because of coincidence of some of the lines inside A.

It would require further study to determine the importance of this effect. The method of this paper could be modified to take it into account; or if the method is used in its present form, the solution can be examined and appropriately modified to take account of the above effect.

3. Total tonnage from all origins to all destinations has been adopted as the criterion, without distinction of types of supplies.

The destinations used in Figs. 7 and 8 have good lateral rail and road connections, so that it appears reasonable to consider the total amount received. However, individual origins or destinations can be considered, especially if it is desired to take special categories of supplies into account. As an example, in Figs. 7 and 8 Roumania may be considered as originating POL. (The outbound flow is greater than the Roumanian rate of POL production, but storage could make up the difference for some months.) If desired, the flow of this POL can then be

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traced through the network to the destinations. There are several possible routings of the POL that are consistent with the traffic patterns indicated.

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Appendix

THE FLOODING TECHNIQUE

This Appendix illustrates how a traffic pattern for a maximal flow in a rail network can be determined by making use of the division-to-division capacity model discussed in the preceding text.

The method illustrated here (see Figs. 10-13) is the "flooding technique," which is more fully described in Ref. 1. It can happen (although not often in applications) that a single application of the method does not produce the maximum flow. However, it is easy to check whether the maximum flow has been obtained. If not, appropriate modifications can be made. It is believed that the method, with common sense modifications indicated by individual problems, is adequate for networks occurring in practice, of the approximate size considered in this paper. Methods which are mathematically guaranteed to produce the maximum flow can be found in Refs. 3 and 4. The methods discussed in these references are closely related to linear programming techniques.

In order to illustrate the application of the procedure, the following assumptions are made:

1. Division-to-division capacities are as indicated in the boxes in Figs. 10-13, except that USSR divisions 28 and 51 and the Roumanian railways are assumed nonoperative (for example isolated by rail cuts).

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The capacities used are the same as in Figs. 7 and 8.

2. Sources of supplies (or origins) are Divisions 8 and 10 in Russia.
3. To simplify the exposition, destinations will be taken as Divisions 1 and 4 in Poland. (Other Satellite divisions can be reached only through these, in the present setup.)

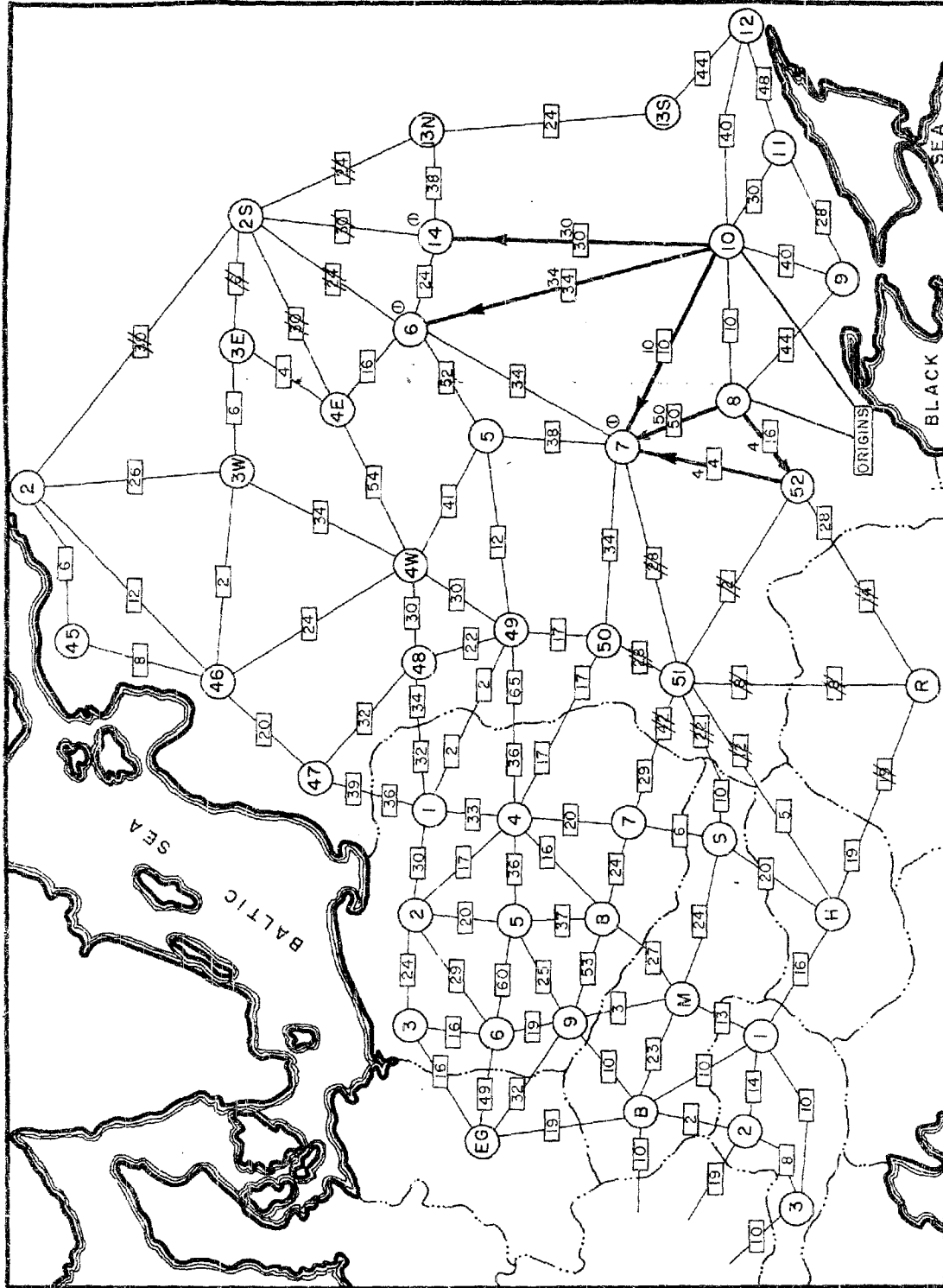
Figs. 10-13 are work sheets showing how the maximal flow is determined; the final outcome has already been shown in Fig. 9. With a little practice the work can all be done on a single sheet, and some of the steps can be telescoped.

Step 1 (see Fig. 10). The first step is to "forward" from each origin the maximum possible outbound flow. Thus 10 units* are sent from Division 10 to Division 7, 34 from 10 to 6, and 30 from 10 to 14. (A little thought indicates that there is no point in sending anything to 9, 11, or 12. Possible use of Black Sea transportation is not considered here.) From the origin at 8, 50 units are sent to 7. If the procedure were followed literally, 16 units would also be sent from 8 to 52. However, the only exit from 52 is by way of 7. Hence, the maximum amount of 4 units is pushed from 8 to 7 by way of 52. The pattern has now been pushed

* The unit can be any convenient quantity; here it is taken as 1,000 tons net.

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Fig.10—Example: Step 1



Legend:
 --- International boundary
 --- Railway operating division
 (8) Capacity: 12 each way per day.
 Required flow of 9 per day forward
 destinations (in direction of arrow)
 with equivalent number of returning
 trains in opposite direction
 All capacities in trains
 1000's of tons each way per day
 Origins: Divisions 8 and 10 in USSR
 Destinations: Divisions 1 and 4 in Poland, thence
 west or south

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as far as the "first stage divisions," which are marked (1): Divisions 6, 7, and 14. At the end of Step 1 the situation is then as indicated in Fig. 10.

Step 2 (Fig. 11). Forward as much as possible from the first-stage divisions. In doing this, the guiding principle, here and at later steps, is to forward from the first-stage divisions in the order of increasing forwarding capacities.* (Individual situations may indicate modifications of this procedure.) The total forwarding capacity for Division 6 is 68, for Division 7 is 72, and for Division 14 is zero (there is no point in going to Division 13). Since nothing can be sent forward from 14, the procedure is to send as much as possible to another Stage 1 division, so 24 units are sent to 6. This is all that can be shipped out of 14, so there is an excess of 6 units (marked 6X) at Division 14.

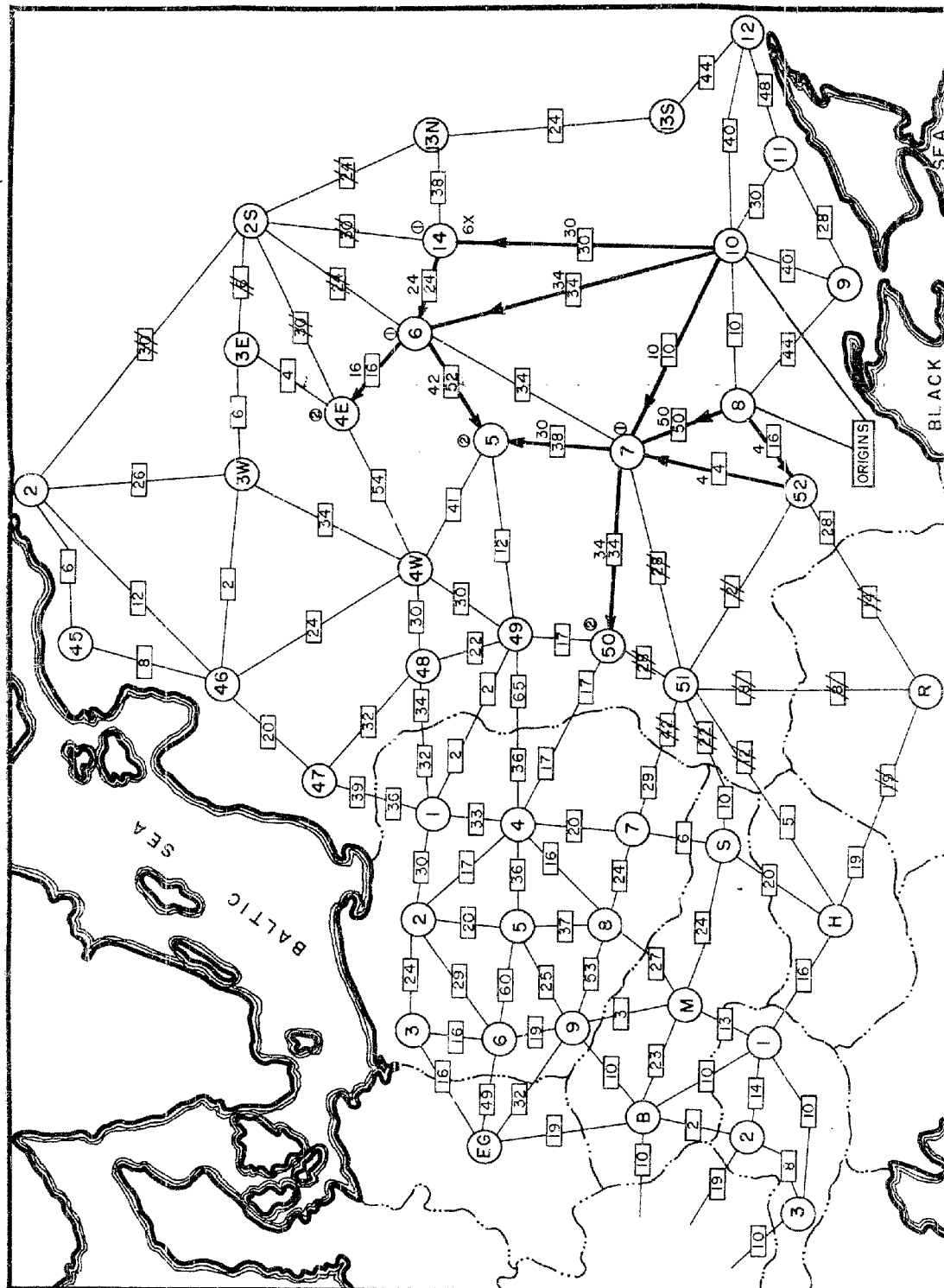
Division 6 is next in order; it now has a total of 58 units entering; 16 units are sent to 4E and 42 to 5, obtaining a balance at 6. At this stage, some judgment was used; had 52 units been sent to 5 and only 6 to 4E, a readjustment would have been necessary at a later stage.

Next, Division 7 is considered; it has 64 units entering; 34 units are sent to Division 50, and 30 to Division 5. The second-stage divisions 50, 5, and 4E have now been reached and the situation is shown in Fig. 11.

* "Forwarding capacity" means capacity to divisions which have not yet been reached.

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Fig. 11—Example: Step 2



Legend:

— ... —

International boundary

(8)

Railway operating division

9

Capacity: 12 each way per day.
 Required flow of 9 per day toward
 destinations (in direction of arrow)
 with equivalent number of returning
 trains in opposite direction

All capacities in trains
 1000's of tons each way per day

Origins: Divisions 8 and 10 in USSR

Destinations: Divisions 1 and 4 in Poland, thence
 west or south

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Step 3 (Fig. 12). Forward units from the second-stage divisions. First 16 units are sent from 4E to 4W, achieving a balance at 4E. Next 17 units are sent from 50 to 4 Poland and 17 units from 50 to 49. Finally 12 units are sent from 5 to 49 and 41 from 5 to 4W. The situation is then as shown in Fig. 12. Division 5 is marked 19X, since 72 units enter and only 53 can leave.

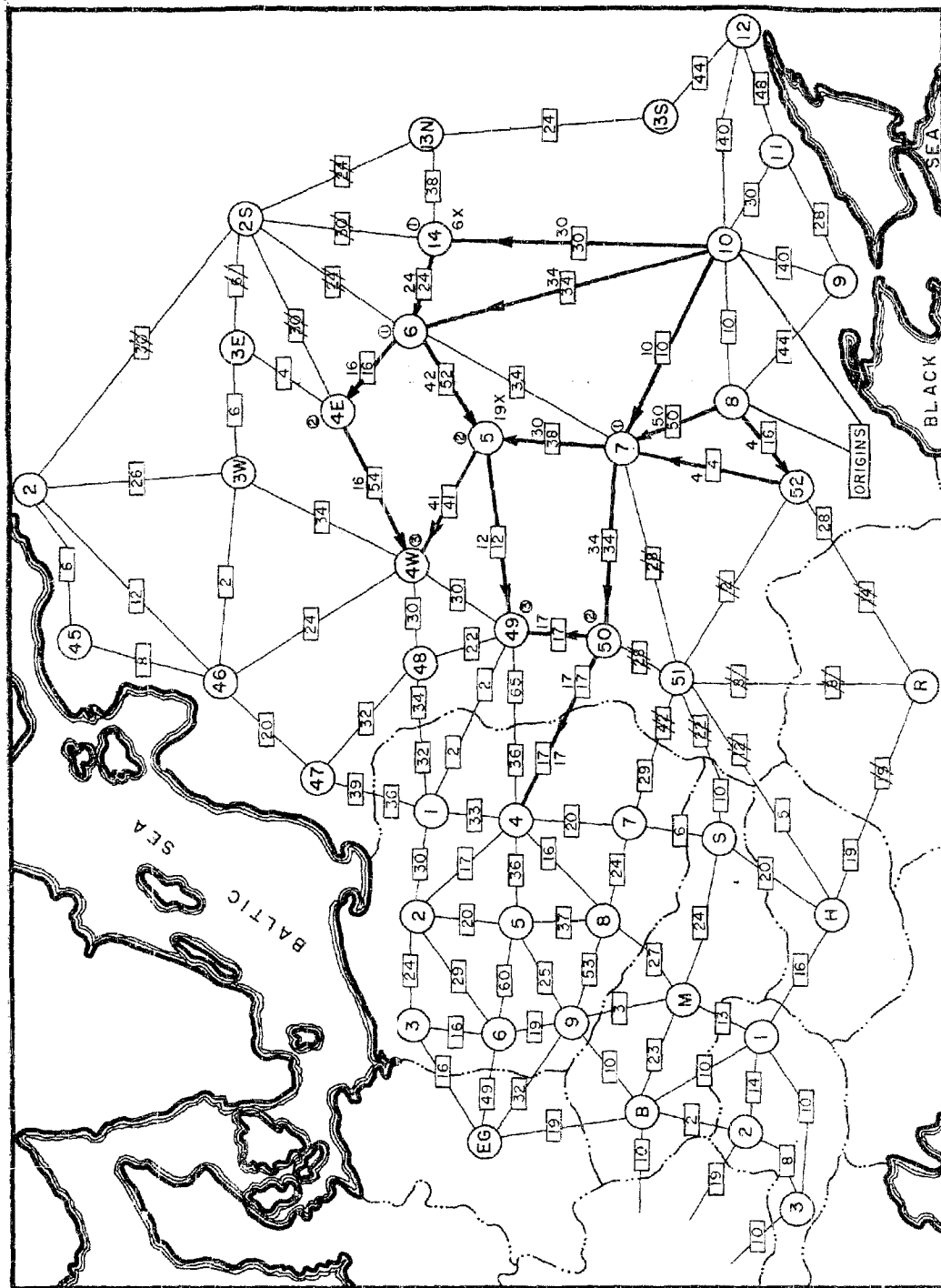
Step 4 (Fig. 13). Units are forwarded to fourth-stage divisions; then it is easy to forward all units through to the destinations, as shown in Fig. 13.

Final Step. Remove the excess flow at Divisions 5 and 14. This can be done in a number of ways by simply subtracting out the extra flow. A completed pattern is shown in Fig. 9. In this pattern the arrows indicate only the direction of traffic bound for the destinations; to achieve a balanced flow, each link carries an equal number of returning trains in the opposite direction.

The fact that the flow achieved in Fig. 9 is maximal can be recognized by the fact that the links 6-4E, 5-4W, 5-49, and 7-50 are each completely saturated with traffic from east to west, and removal of these links completely severs the origins from the destinations. It can be shown (see, for example, Ref. 2) that when the flow is maximal there is always such a set of saturated links.

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Fig. 12—Example: Step 3



Legend:

--- International boundary

(B) Railway operating division

9
12

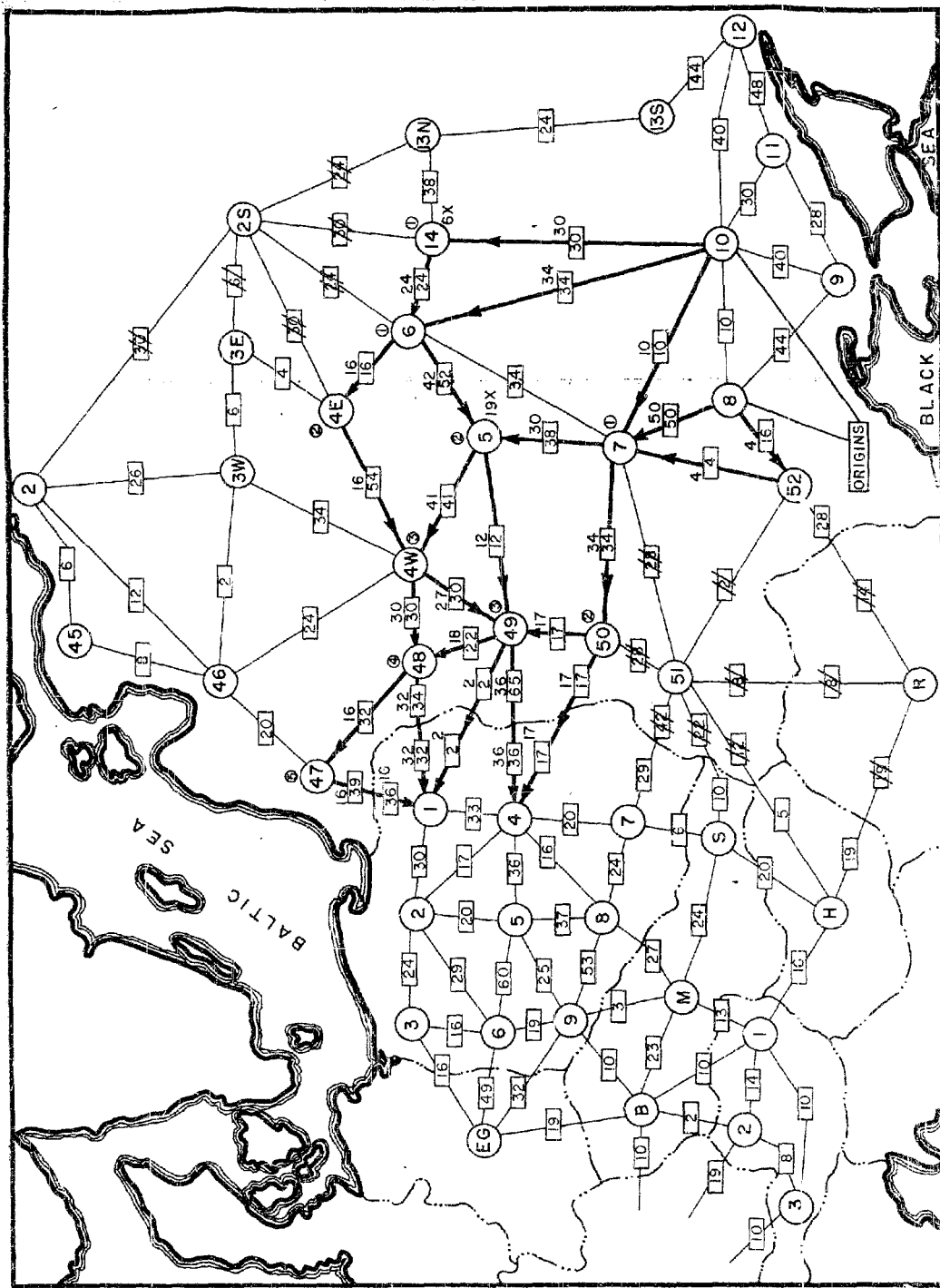
Capacity: 12 each way per day.
Required flow of 9 per day toward
destinations (in direction of arrow)
with equivalent number of returning
trains in opposite direction

All capacities in trains
in 1000s of tons each way per day

Origins: Divisions 8 and 10 in USSR

Destinations: Divisions 1 and 4 in Poland, thence
west or south

Fig. 13— Example: Step 4
and continuation



Legend:
--- International boundary
—— Railway operating division
(8) Capacity: 12 each way per day.
9 Required flow of 9 per day toward destinations (in direction of arrow) with equivalent number of returning trains in opposite direction
All capacities in /1000s of tons/ each way per day
Origins: Divisions 8 and 10 in USSR
Destinations: Divisions 1 and 4 in Poland, thence west or south

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DEPARTMENT OF THE AIR FORCE
11TH WING

13 May 1999

11 CS/SCSR (MDR)
1000 Air Force Pentagon
Washington, DC 20330-1000

Mr. Walter Nelson
Rand
Head, Classified Information Services
1700 Main Street
PO Box 2138
Santa Monica, CA 90407-2138

Dear Mr. Nelson:

This responds to your 9 April 1999 letter, requesting a Mandatory Declassification Review on the following document:

Fundamentals of a Method for Evaluating Rail Net Capacities, October 24, 1955

AD-093 458

The attached request has been reviewed by the appropriate Air Force activity and have no objection to declassification and release.

Two of the three copies forwarded to this office are being returned (RM-1573, copies 1 and 2), copy 3 will be filed in this office for future reference.

Any questions regarding the review of this document may be addressed by contacting the undersigned at (703) 696-7265 or DSN: 426-7265. Please reference Air Force case # 99-MDR-006.


JOANNE MCLEAN
Mandatory Declassification Review Manager

2 Attachments

1. NAIC/IA Memo, 23 Apr 99
2. Records for Review (C)

THIS LETTER IS UNCLASSIFIED STANDING ALONE

Completed
17 May 2000
B.W.

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